Demonstration of Spacecraft Fire Safety Technology

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During the Constellation Program, the development of spacecraft fire safety technologies were focused on the immediate questions related to the atmosphere of the habitable volume and implementation of fire detection, suppression, and post-fire clean-up systems into the vehicle architectures. One of the difficulties encountered during the trade studies for these systems was the frequent lack of data regarding the performance of a technology, such as a water mist fire suppression system or an optically-based combustion product monitor. Even though a spacecraft fire safety technology development project was being funded, there was insufficient time and funding to address all the issues as they were identified. At the conclusion of the Constellation Program, these knowledge gaps formed the basis for a project proposed to the Advanced Exploration Systems (AES) Program. This project, subsequently funded by the AES Program and in operation since October 2011, has as its cornerstone the development of an experiment to be conducted on an ISS resupply vehicle, such as the European Space Agency (ESA) Automated Transfer Vehicle (ATV) or Orbital Science's Cygnus vehicle after it leaves the ISS and before it enters the atmosphere. The technology development efforts being conducted in this project include continued quantification of low- and partial-gravity maximum oxygen concentrations of spacecraft-relevant materials, development and verification of sensors for fire detection and post-fire monitoring, development of standards for sizing and selecting spacecraft fire suppression systems, and demonstration of post-fire cleanup strategies. The major technology development efforts are identified in this paper but its primary purpose is to describe the spacecraft fire safety demonstration being planned for the reentry vehicle.

I. Introduction and Background

Development of fire safety technologies for space flight systems is an on-going process. Even operational systems, such as the recently retired Space Shuttle or the International Space Station (ISS) are not static but undergo various reconfigurations and modifications on practically every mission or expedition. Any change to the operating environment or protocol is evaluated to determine its impact on the rest of the spacecraft, including any change in the susceptibility for ignition, increase in material flammability, or the ability to respond to a fire should one occur. NASA recognized the need for the continued investigation and development of spacecraft fire safety technologies and included such investigations in the Fire Prevention, Detection, and Suppression (FPDS) technology development project within the Exploration Technology Development Program sponsored by NASA's Exploration System Mission Directorate (ESMD). The goal of this project was to develop technologies that will ensure crew health and safety on exploration missions by reducing the likelihood of a fire, or, if one does occur, minimizing the risk to the crew, mission, or system. The project addressed all aspects of fire safety aboard crewed exploration systems. Areas addressed include (1) fire prevention and material flammability, (2) fire signatures and detection, (3) fire suppression, and (4) post-fire response.

Many of the tasks conducted in the FPDS project were developed to meet specific needs identified by the designers of the Orion, Altair, and Lunar Surface Systems vehicles and habitats in the Constellation Program. Investigators frequently worked closely with designers of the Environmental Control and Life Support (ECLS) system to extrapolate existing data and knowledge of microgravity combustion to the spacecraft fire detection and

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suppression (FDS) system. There is a wealth of data for many of these technologies for terrestrial fire safety applications. However, given the unique spacecraft environment that includes microgravity, increased oxygen mole fractions, reduced ambient pressures, lack of egress, etc., extrapolation of these data was tenuous. When low-gravity data was available, it was frequently obtained at conditions or length scales that were different than those being considered; in other instances, there was a complete lack of data. From the standpoint of the technology developer, the lack of relevant data would have been addressed by defining and conducting a task to obtain the needed information. However, the pace of the design and development of the Orion and Altair vehicles prohibited this approach. By the time the information was obtained, the immediate need would most likely have passed. All this was done with the intention of re-visiting important technology gaps later in the design process with the risk that, once additional knowledge was obtained, the decisions made using incomplete information might have to be changed.

As the next exploration missions are being planned, there is a window of opportunity to address gaps in our spacecraft fire safety knowledge by obtaining the required data and conducting more detailed analysis. The goal of the Advanced Exploration Systems Program is to advance exploration systems and validate operational concepts for future human missions beyond Earth orbit. A key feature of projects in this program will be the demonstration of prototype systems in ground test beds, field tests, underwater tests, and ISS flight experiments to verify their performance. The Spacecraft Fire Safety Demonstration (SFS Demo) project began in October 2011 with the objective to develop and demonstrate technologies for spacecraft fire safety that have been shown to influence major design decisions regarding the ECLS and FDS systems. Researchers and engineers at NASA John H. Glenn Research Center (GRC), Johnson Spaceflight Center (JSC), Marshall Space Flight Center (MSFC), and the Jet Propulsion Laboratory (JPL) are actively participating in this work to take advantage of the expertise and collaborations that have been developed over the years. These technologies being developed and the demonstrations planned for this project are described in this paper. The current status of the fire safety demonstration experiment is also discussed.

II. Spacecraft Fire Safety Technologies and Demonstrations

The project funded by the Advanced Exploration Systems program was formulated to develop and demonstrate spacecraft fire safety technologies in relevant environments. The keystone of these demonstrations is a large-scale fire safety experiment conducted on an International Space Station (ISS) re-supply vehicle after it has undocked from the ISS and before it enters the atmosphere. This experiment will be discussed in subsequent sections. However, this is not the only technology development effort being conducted in this project. The breadth of tasks include investigation of low-gravity material flammability in ground-based facilities and development of advanced sensor technologies such as particulate monitors for fire detection and gaseous combustion product monitors for both fire detection and monitoring post-fire cleanup.

Table 1 shows the technologies being advanced in the Spacecraft Fire Safety Demonstration project[3] and the associated demonstrations that are planned to be conducted. In the following sections, major aspects of each of these tasks will be briefly discussed, with references to more complete descriptions in existing literature. The specific tasks that are directly supporting the Spacecraft Fire Safety Demonstration experiment will be highlighted and discussed in additional detail.

A. Material Flammability Tasks

NASA-STD-6001A Test 1, the Upward Flame Propagation Test, is the primary test to screen spacecraft materials for flammability before they can be used on spacecraft.[1] Out of necessity, these tests are conducted in normal gravity in a large closed chamber in which the pressure and oxygen concentration can be set to the desired test condition. A relatively small sample (5 cm x 33 cm) is held in a sample holder and ignited at the bottom by a chemical igniter[4]. The material passes the test, *i.e.*, is considered to be non-flammable, if the flame self-extinguishes before it propagates 15 cm. During the Constellation Program, this test was extended to not only determine whether the material passed or failed at a specific oxygen concentration and ambient pressure but also to determine the maximum oxygen concentration at which a material could pass Test 1. This was defined as the maximum oxygen concentration (MOC) and was determined for a large number of materials typically used in spacecraft [2, 3].

As part of the FPDS technology development project, tests were conducted in the Zero Gravity Facility at NASA GRC in a combustion wind tunnel. Data have shown that for relevant spacecraft materials, the MOC limits in both

[3] In this paper, the project is titled the *Spacecraft Fire Safety Demonstration Project* with the flight experiment called the *Spacecraft Fire Safety Demonstration.*

[4] A silicone igniter is used if the oxygen concentration is greater than 50% by volume.

low-g (with a convective flow) and in partial-g than the MOC limits determine in normal gravity. Typical results from Olson *et al.* [4] for charring materials have shown that the differences can be as large as 4% O_2 by volume for thin charring materials. Tests conducted in partial-gravity have shown that these MOC limits were not simple interpolations of the behavior in normal and low-(zero-) gravity but were even lower than those in low-gravity [5, 6].

The Burning and Suppression of Solids (BASS) experiment made use of the Structure and Liftoff in Combustion Environment (SLICE) experiment hardware that is installed in the Microgravity Science Glovebox (MSG). In the BASS experiment, small sample materials (cotton-fiberglass, Nomex, and Ultem samples 1- and 2-cm wide and PMMA spheres 1- and 2-cm in diameter) can be burned to evaluate flammability limits, similar to what is done in the Zero Gravity facility. Because the experiment is operated in the MSG, the samples are limited to those that burn in 21% oxygen by volume. The testing of small scale samples is useful because it elucidates the effect of the material shape on low-g flame behavior and enhances knowledge of microgravity combustion. However, the scaling of the heat release from a flame and the heat loss mechanisms make extrapolation of these small sample data to the larger samples typical of spacecraft fire safety applications more difficult. Of course, one of the advantages of the SFS Demonstration experiment is that the sample size can be 5 cm x 33 cm and larger which would allow the flame to become more developed. As part of the material flammability work in the SFS Demo experiment, the team is evaluating the technical, cost, and schedule feasibility of modifying the BASS experiment to burn larger samples, closer in size to those planned for the SFS Demo experiment. Depending on timing, this could be a risk mitigation experiment for the SFS Demo experiment because preliminary flammability limits could be evaluated as well as sample configuration, ignition mechanism, imaging, *etc*. Currently, there is not a plan to fly this experiment but initial plans would be ready if the opportunity became available.

B. Fire Signature and Detection Tasks

One of the major tasks of the FPDS project, the predecessor to the SFS Demonstration project, was the identification of gaseous and particulate signatures for typical spacecraft fires. The knowledge of the fire signature, *i.e.*, the characteristic marker for a fire that is monitored by a sensor, is essential prior to developing suitable detectors. Even if a detector is sensitive to a prominent fire signature, proper deployment is required to provide early warning of a fire. Knowledge of common fire signatures in low- and partial-gravity including smoke, gaseous products, temperature, IR signature, or flicker frequency is probably the largest technology gap in the detection of spacecraft fires. Early spacecraft, such as Mercury, Gemini, and Apollo had no dedicated fire detection and relied completely on the crew senses. Skylab used an array of ultraviolet detectors throughout the open volume of the spacecraft. The Shuttle used ionization smoke detectors as do the Russian modules of the International Space Station. The U.S. modules have photoelectric smoke detectors. The design of these spacecraft fire detectors has generally been based on knowledge of terrestrial fire detectors. Recent experiments on the ISS, the Smoke Aerosol Measurement Experiment (SAME) and the reflight (SAME-R), have focused on quantifying the size distribution of smoke particulate produced in low-gravity by materials typically found in spacecraft electronics and in the cabin as described in [7-11]. These data continue to be analyzed and will allow for the rational design of advanced smoke detectors that yield additional information about the smoke aerosol and provide improved nuisance source rejection.

Using these gaseous and particulate fire signatures, the development of small, low-power gaseous and particulate sensors would allow them to be distributed throughout a spacecraft or habitat to quickly detect and potentially locate a fire and monitor the fire response and cleanup. In fact, they could be integrated into the atmospheric monitoring equipment to provide more complete and localized information on the spacecraft atmosphere.

As part the of SFS Demo project, the team is investigating the feasibility of implementing one or more of the advanced fire detection technologies in a reflight of the Smoke Aerosol Measurement Experiment, currently designated as SAME-3. This could include monitors for gaseous fire signatures could aerosol detectors, depending on the complexity of implementation. The SFS Demo project team is working with the SAME development team to assess the integration of these technologies into the SAME hardware when installed in the Microgravity Sciences Glovebox on ISS. The outcome of this effort would be recommendations for the most relevant and useful diagnostics for this experiment as well as an estimated cost and schedule for implementation. Currently, a SAME-3 experiment that continues the SAME objectives while adding relevant diagnostics is a potential for implementation within the ISS Research Project beginning in FY15.

C. Fire Suppression Tasks

During the FPDS project, a task was initiated to characterize fine water mist fire suppression technology so that data were available to use in trade studies for fire extinguishers on exploration vehicles. While performing this work, this technology was also selected by the ISS as a potential replacement for the gaseous CO_2 fire extinguishers on

ISS. While GRC personnel are supporting this work, it is not directly funded by the SFS Demo project. However, if vehicle capability and experiment operation allows, a fire suppression technology could be demonstrated in future SFS Demo experiments.

The ISS Fine Water Mist Portable Fire Extinguisher project highlighted the fact that there are no standard spacecraft fires with which to evaluate fire suppression systems, or any fire safety technology. Terrestrial fire safety applications have demonstrated that the definition of a design fire is a critical step in the application of performance-based fire safety strategies. While the definition of these standards is beyond the scope of the SFS Demo project, many of the tools being developed within the project, such as the evaluation of the environment conditions in a sealed chamber after a fire [X] and the analysis of a survivable fire [X], are useful in this analysis. These analyses of fire scenarios will be adapted to the various design reference missions as NASA continues its plans for space exploration.

D. Post-fire Response and Monitoring Tasks

An effective post-fire response should integrate the fire extinguisher, a filtering respirator for emergency breathing, an emergency air purifier, and a contingency air monitor. Proper development of these technologies requires that the pressure, temperature, and composition of the atmosphere after a fire be specified. The composition of the atmosphere includes not only the concentration of relevant combustion products but also the dispersed suppression agent, particles, *etc*. Determining a suitable post-fire challenge with which to develop and verify the emergency response equipment and procedures has been a major technology development task. A test procedure developed by Zuniga *et al.* [14] and further analyzed by Ruff *et al.* [15] uses a generic spacecraft "fuel" that is a mix of polymer shavings produced from materials typical of those found in avionics and electronics system. Rather than attempting to scale the post-fire atmosphere in a spacecraft, this mixture was developed based on electrical components found in a typical avionics package.[16-17] The amount of this mixture burned in a test is one of the test variables and could be used to scale results to a specific spacecraft volume [14-15]. The plan for the SFS Demo Project is to continue to develop suitable instruments and conduct post-fire tests at NASA-WSTF. As in previous tests, the plan is to test simultaneously multiple instruments that monitor gaseous species and particulate species, along with reference instruments, to thoroughly evaluate and compare the technologies. Not only does this provide a characterization of a post-fire environment, it also allows the evaluation and comparison of technologies for post-fire monitoring.

Another aspect of post-fire response is rapid cleanup from the fire. A self-contained system that could rapidly clean-up particulate and gaseous combustion products from the spacecraft atmosphere would off-load that requirement from the rest of the ECLS air revitalization system thereby reducing complexity and consumables from the larger, more complete system. This type of device, frequently called a "smoke eater", is being developed within the SFS Demo project. Depending on the rate of technology development and timing of the flight, this instrument could be implemented in the Spacecraft Fire Safety Demonstration flight experiment.

III. Spacecraft Fire Safety Demonstration

As discussed in previous sections, the objective of NASA's Advanced Exploration Systems Program is to advance and demonstrate technologies such that they can be implemented on future exploration systems. The objective of the Spacecraft Fire Safety Demonstration Project is to advance these technologies through ground- and flight-based demonstrations with the keystone demonstration being a space flight experiment conducted on a re-supply vehicle for the International Space Station (ISS) after it has undocked from the ISS and before it enters the atmosphere. The definition and conceptual design of this experiment has been the primary task of the Spacecraft Fire Safety Demonstration Project both in terms of visibility and resources.

The development of this experiment requires a breadth of different tasks. First, the science and technology requirements for the experiment need to be identified. These are then translated into engineering requirements and expanded to develop engineering drawings and operation concepts for the experiment. In this case, selection of the resupply vehicle in which to conduct the experiment is another key task. This prompted the project team to conduct a trade study to identify vehicles suitable to conduct this experiment.

A. Vehicle Trade Study

The candidate vehicles for this experiment include any of the current or planned ISS resupply vehicles such as the ATV, HTV, or Cygnus[5]. The SFS Demo project team evaluated various characteristics of these vehicles including:

- Volume of the vehicle
- Weight/CoG restrictions
- Availability of on-board power
- Availability of communication
- Data downlink options
- Experiment mounting options
- Concept of operations
- Command and control options
- Allowable pressure rise
- Possible experiment configuration
- Availability of ground support
- Launch schedule

To date, the ATV and Cygnus vehicles appear to be viable options for this experiment.[6] Early in the development of the project, the European Space Agency (ESA) became interested in this experiment. Dr. Olivier Minster, Senior Physical Scientist in the Directorate of Human Spaceflight for the European Space Agency formed an international topical team chaired by Professor Grunde Jomaas (Denmark Technological University) and Professor Jose Torero (BRE Trust/RAEng Chair in Fire Safety Engineering in the School of Engineering at the University of Edinburgh). This team consists of 14 researchers from the European, Japanese, Russian, and U.S. spacecraft fire safety communities to define research that would be possible from such a low-gravity fire safety experiment.[7] This group has developed the initial science and technology requirements for this experiment. Concurrent with this activity, ESA initiated an ATV Feasibility Study to assess the feasibility of conducting this experiment on ATV. The results of this study have been released and from a technical and operational viewpoint, the experiment itself was found to be feasible. The experiment concept to be discussed in the next section is based on a baseline configuration in the ATV although the experiments to be conducted in other vehicles are anticipated to be similar. The SFS Demo Project Team has had detailed discussions with personnel from Orbital Sciences and reached similar conclusions. Because the Cygnus vehicle is considerable smaller than ATV, the material flammability experiments may be conducted on more than one flight in a smaller experimental facility.

B. Experiment Concept

The concept for this experiment focuses on conducting two types of material flammability tests that would be performed sequentially and could proceed autonomously, although down- and up-link capability between tests would be desirable. A CAD model of the concept of the experimental configuration mounted on the front of racks is shown in Fig. 1. The hardware consists of the experiment module, the avionics module, and the battery module. As shown in this figure, the experiment module is mounted to the front of the ATV racks while the battery and avionics modules are mounted within adjacent racks. The top and bottom structures on the experiment module are the fan unit on the top and the flow straightener unit on the bottom. The airflow is from the bottom to the top of the experiment module. Nomex covers surround the experiment to allow a more uniform flow across the samples, maintain a clear flow path within the experiment module, and lastly to prevent burning debris from interacting with the rest of the cargo.

The objective of the first set of tests is to investigate the low-gravity Maximum Oxygen Concentration (MOC) flammability limits in long-term low gravity. The configuration for these experiments consists of nine samples of varying materials (denoted flammability samples) each having dimensions of approximately 5 cm wide by 30 cm long and shown on the left in Fig. 2. These samples emulate the configuration used in NASA-STD-6001 Test 1.

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[5] The SpaceX Dragon vehicle also will re-supply ISS but it is recovered for re-use. Combustion products from this experiment would enter the vehicle and contaminate the contents thereby complicating the recovery and refurbishment of the vehicle.

[6] In May 2012, funding and schedule concerns eliminated the feasibility of conducting the Spacecraft Fire Safety Demonstration experiment on ATV-5, the last planned ATV mission. One or more experiments similar in concept to that discussed in this paper are being planned for implementation on Orbital Science's Cygnus vehicle.

[7] Members of the Spacecraft Fire Safety Topical Team are listed in the Acknowledgements.

Each sample is ignited at the bottom using a hot wire. The oxygen concentration in the vehicle will be nearly 21% by volume -- the same as in the ISS when the hatch was closed. The materials would be selected to be near their normal-gravity or hypothesized low-gravity maximum oxygen concentration in 21% O_2. This complicates the selection of sample materials because most materials relevant for spacecraft do not have flammability limits near 21% oxygen by volume.

Camera images would be the primary diagnostics for these tests as the intended result is primarily to determine whether the flame propagates or self-extinguishes. However, an anemometer would be mounted upstream of each sample so the air velocity would be known and available for post-test analysis.

The second test will investigate flame spread over a panel of thin material approximately 0.3 m wide by 1.0 m long, shown in the right in Fig. 2. As in the previous tests, the ignition method would be a hot wire along the upstream edge. This material will be expected to burn at the anticipated cabin atmosphere. The objective of this test is to quantify the flame development over a large sample in low-gravity. This sample will be more heavily instrumented with multi-view video, thermocouples, and radiometers so that the data can be used to verify numerical simulations of fire spread and development in low-g.

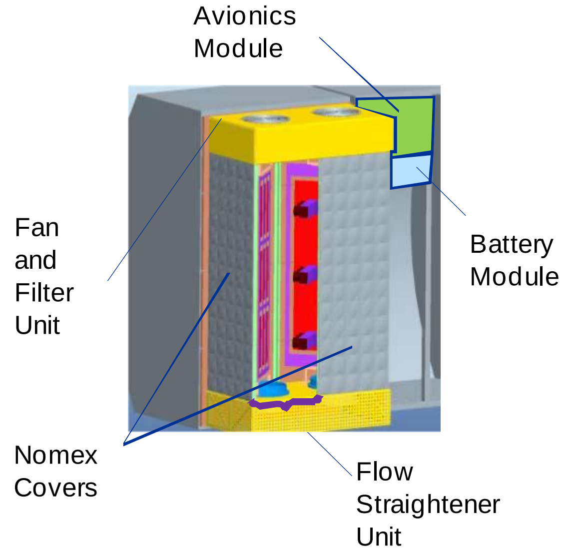

Figure 1. CAD model of the components of the Spacecraft Fire Safety Demonstration experiment mounted on the front of an ATV rack. *The experiment module, avionics module, and battery module are shown.*

Additional diagnostics to be included in the flow straightener and fan units include oxygen sensors, thermocouples, and CO and CO_2 sensors. In addition to filtering particulate, the filter unit could contain the recently developed CO sorbent materials developed as part of the post-fire monitoring task.

C. Sample Selection

Identifying samples that have flammability limits in the vicinity of 21% oxygen by volume is not trivial. An additional consideration is that re-entry vehicles, in general are designed to operate within a rather narrow pressure range. Increasing the internal pressure due to the heat release from a combustion event would trigger the opening of a pressure relief valve. While this is an accepted safety precaution, it is not acceptable for an on-board experiment to cause a pressure relief valve to open as part of normal operations. Therefore, this experiment is constrained both by the required flammability limit of the fuel as well as the rate of heat release. Current plans are to use a thin cellulosic material that typically burns easily in 21% oxygen but alter its flammability limit using a backing material of appropriate composition and thickness. Ceramic fabric and aluminum foils of various thicknesses are currently being evaluated.

Given the volume of a closed chamber, the pressure rise created by the combustion of a known mass of fuel is a simple calculation. The complication is that the time history of the pressure rise depends on the balance between the heat release rate of the combustion process and the rate of heat transfer to the cargo and vehicle structure. A transient analysis of this phenomenon can be developed but a detailed verification of this model is required. An

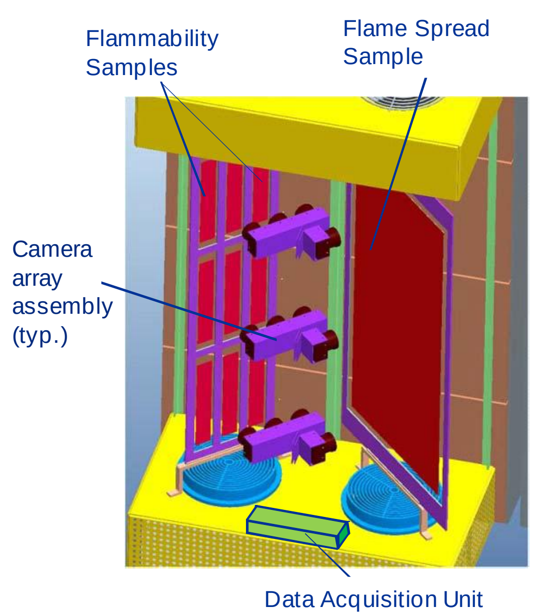

Figure 2. Experiment Module for the Spacecraft Fire Safety Demonstration showing the flammability samples (left) and the flame spread sample (right). *The camera array assemblies and data acquisition unit is also shown.*

experiment is being conducted in a vacuum facility at NASA GRC in which full-scale samples for the SFS Demonstration experiment can be burned and the rise in gas temperature and pressure rise measured. Data from these tests will be used to identify the relevant heat transfer mechanisms and verify code predictions. This will then be applied to the experiment in the re-entry vehicle to predict the transient pressure rise and plan the sequence of the experiment.

In addition to sample selection and pressure rise, another important operational issue is that of communications. In general, the communication systems of these vehicles were designed for vehicle command and control, not for downloading large quantities of video data. This adds operational complexity by allowing sufficient time to downlink a series of smaller data files. This assumes, of course, that the experiment can make use of the vehicle communication system. The experiment complexity is compounded if our project must supply its own transmitter and communications software. Perhaps the largest challenge is obtaining the proper alignment of resources (both monetary and workforce) and schedule to allow the experiment to be performed within the operating constraints set by the AES Program Office. Nevertheless, this experiment would be a landmark for spacecraft fire safety with the data and subsequent analysis providing much needed verifications of spacecraft fire safety protocol for the crews of future exploration vehicles and habitats.

IV. Conclusion

Gaps in spacecraft fire safety technologies were identified during the initial execution of NASA's Constellation Program. Tasks to advance these technologies were sub-divided into a series of ground- and space-based demonstration tasks that fit directly into the objectives of NASA's Advanced Exploration Systems Program. The cornerstone of these demonstrations is a material flammability experiment conducted on an ISS resupply vehicle after it has undocked from the ISS and before it reenters the atmosphere. This experiment will allow the evaluation of practical low-g material flammability phenomena that are important for spacecraft design yet are unobtainable in ISS facilities or other orbital platforms. This experiment has been shown to be feasible on both ESA's ATV and Orbital Science's Cygnus vehicles. Because of the early interaction with ESA, an international topical team has been formed to develop concepts for that experiment and work towards its implementation. An experimental concept is being developed that will investigate oxygen flammability limits and flame spread over a large fuel sample in a long-term low gravity environment. Additional tasks in the Spacecraft Fire Safety Demonstration Project are being conducted to identify sample materials and verify the predictions of pressure rise in the re-entry vehicle during the experiment. In addition to this ground-breaking space flight experiment, several ISS experiments are being defined that could also advance specific fire safety technologies.

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Advanced Exploration Systems Program

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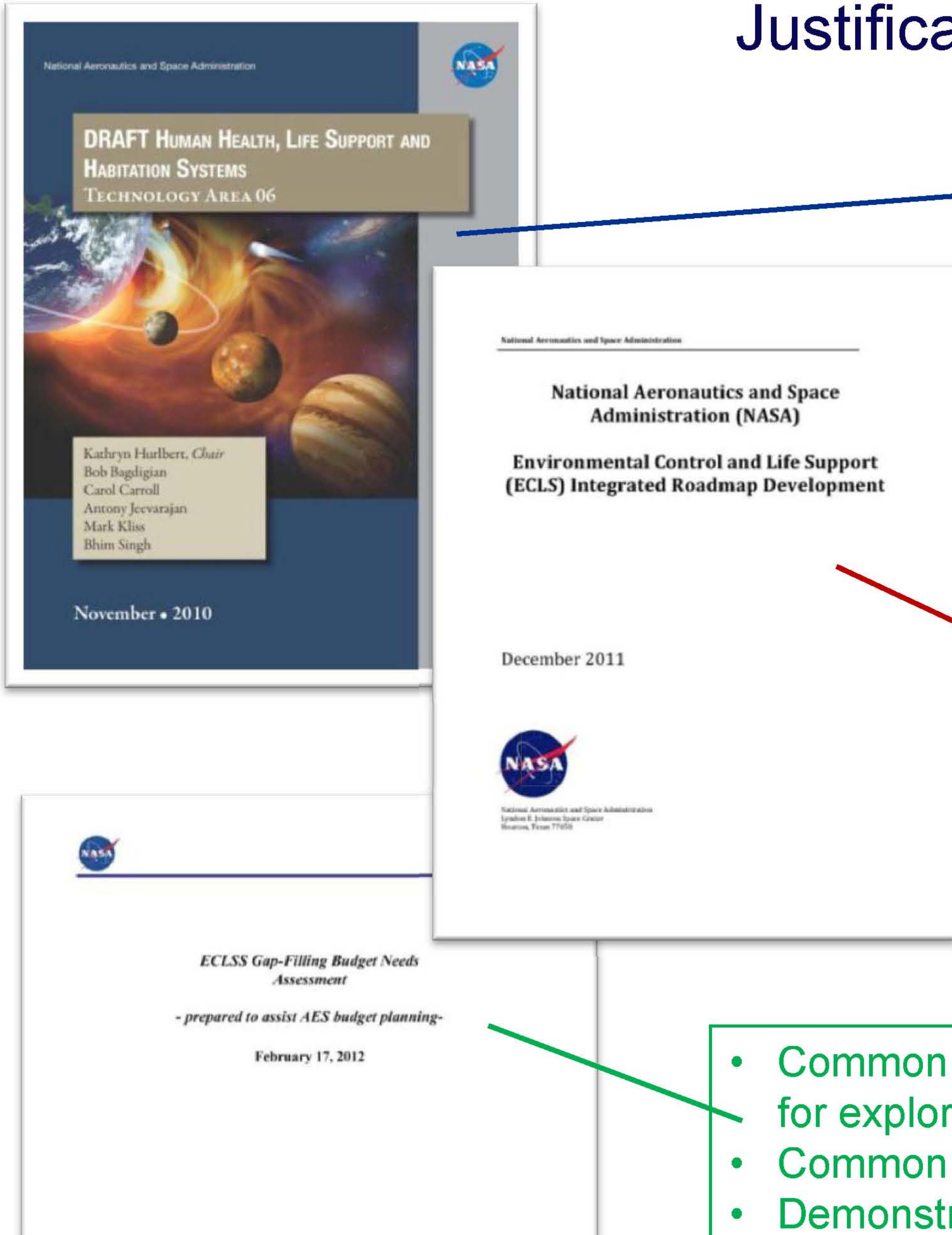
Technology Development for Spacecraft Fire Safety

- The formulation of the Constellation Program highlighted the need to development key environmental control and life support technologies
  - Fire Prevention, Detection, and Suppression (FPDS) project within the Exploration Technology Development Program (ETDP)
- The overarching goal for the FPDS project was to develop technologies to help ensure crew health and safety on exploration missions by reducing the likelihood of a fire, or, if one does occur, minimizing the risk to the crew, mission, or system.
- Significant progress was made in many areas but recent reviews and roadmapping for exploration have continued to highlight needs in spacecraft fire safety

  One of the areas that has been lacking is how to demonstrate these technologies in a relevant environment

Justification


National Aeronautics and Space Administration

DRAFT HUMAN HEALTH, LIFE SUPPORT AND HABITATION SYSTEMS

TECHNOLOGY AREA 06

Kathryn Hurlbert, *Chair*
Bob Bagdigian
Carol Carroll
Antony Jeevarajan
Mark Kliss
Bhim Singh

November • 2010

National Aeronautics and Space Administration (NASA)

Environmental Control and Life Support (ECLS) Integrated Roadmap Development

December 2011

ECLSS Gap-Filling Budget Needs Assessment

- prepared to assist AES budget planning-

February 17, 2012

- *Low- and partial-g flammability limits for spacecraft materials*
- *Hybrid gas and particulate sensors fro fire detectors and post-fire monitoring*
- *Realistic fire challenges*

- Common smoke detectors, fire extinguisher, post-fire response and monitoring equipment
  - Smoke-eater *(Enabling)*
  - Combustion Product Monitor
- Material flammability (margin of safety) at high %O_2
  - Improved detection and suppression to reduce risk *(Enhancing)*

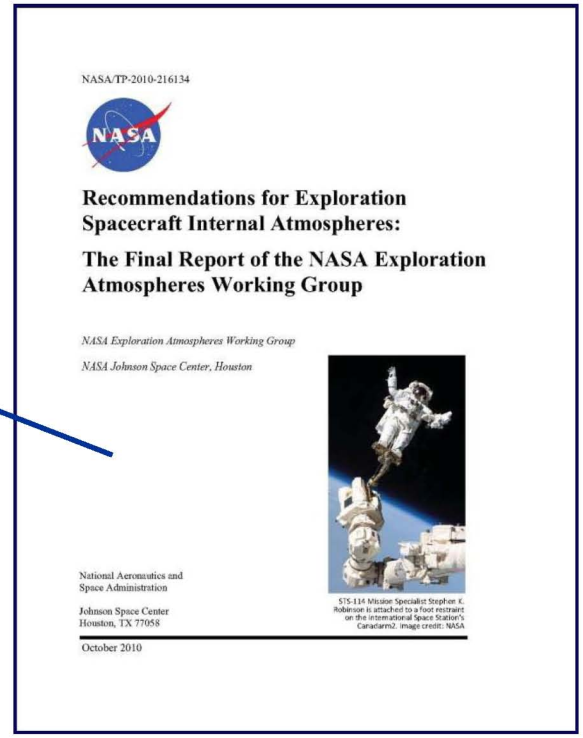
- Common portable fire extinguisher for exploration
- Common Smoke Eater technology
- Demonstrating technologies in SFS Demo

Scalable!

Justification

- Exploration Atmospheres Working Group
  - Formed in 2005 to evaluate habitable atmospheres for Constellation
    - Composed of experts in physiology and medical factors, vehicle and habitat systems, and mission operations (Don Henninger: team lead)
  - Reconvened in 2011 at the request of Mr. Gerstenmaier to:
    - summarize the technical issues associated with atmosphere selection
    - assess habitable atmospheres for current Design Reference Missions, and
    - identify technology needs

- *Low- and partial-g flammability limits for spacecraft materials*
- *Fine water mist fire extinguishers for high %O_2 environments*


NASA/TP-2010-216134

Recommendations for Exploration Spacecraft Internal Atmospheres:

The Final Report of the NASA Exploration Atmospheres Working Group

NASA Exploration Atmospheres Working Group

NASA Johnson Space Center, Houston

STS-114 Mission Specialist Stephen K. Robinson is attached to a foot restraint on the International Space Station's Canadarm2. Image credit: NASA

National Aeronautics and Space Administration

Johnson Space Center
Houston, TX 77058

October 2010

Spacecraft Fire Safety Demonstration Project

Objective:

- Advance spacecraft fire safety technologies identified as gaps by the Constellation Program and in the Exploration Technology Roadmaps
- Demonstrate their performance in a large-scale, low-gravity spacecraft fire safety test aboard an unmanned re-entry vehicle
  – Demonstration of the operational concept could allow future experiments to investigate fire detection and suppression equipment and protocols.

Relevance to Human Space Flight:

The material flammability questions to be addressed in this experiment were identified during the design of the ECLS system for Orion, Altair, and Lunar Surface Systems

- Addresses knowledge gaps that must be resolved for assured protection of a spacecraft from fire hazards

Most U.S. agencies responsible for large transportation systems conduct full-scale fire tests to address gaps in fire safety knowledge and prove equipment and protocols.

FAA full scale aircraft test

Controlled burns of structures

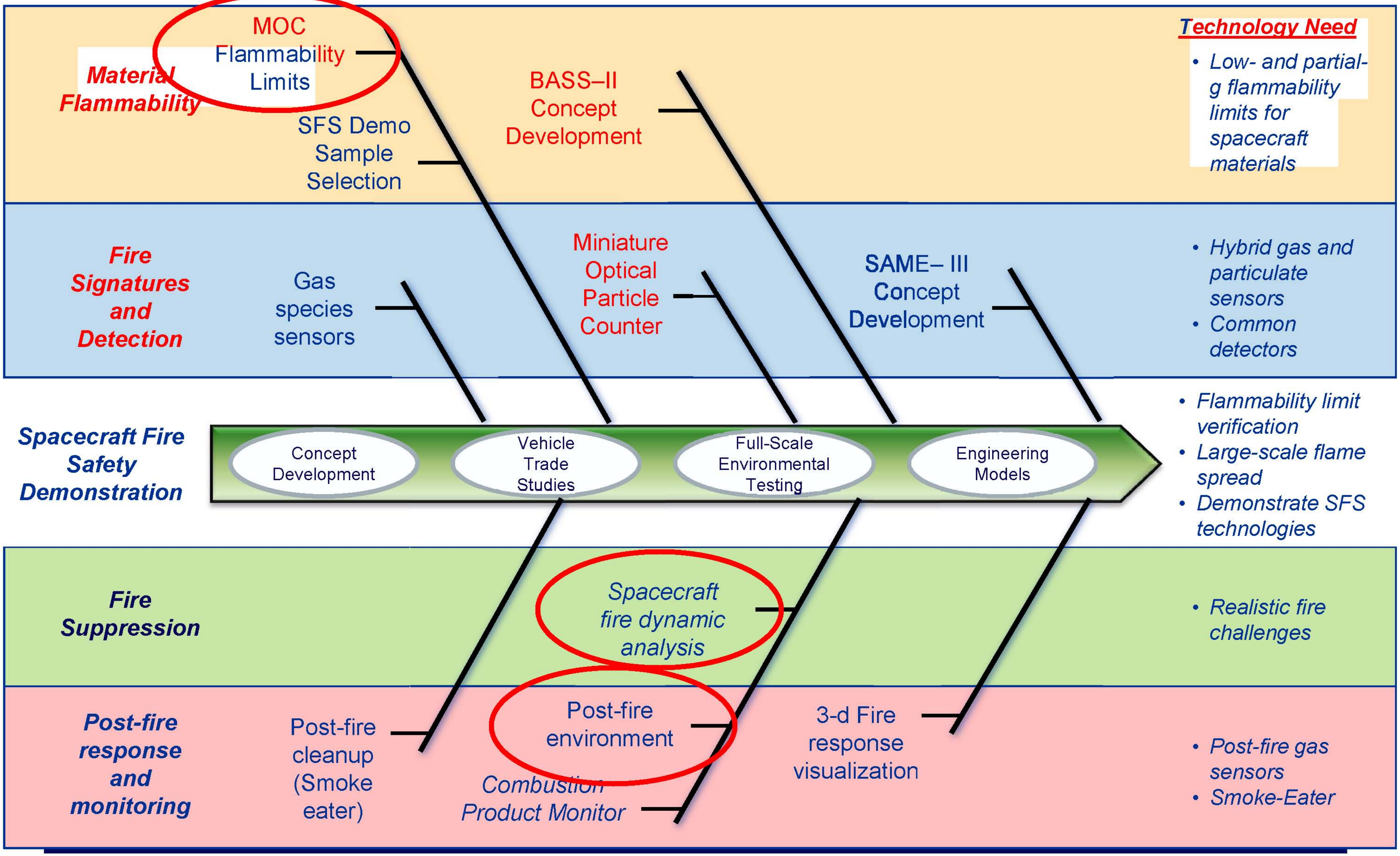
Naval Research Laboratory Ex-USS Shadwell

ESA's ATV approaching the ISS

Orbital Science's Cygnus approaching ISS

Spacecraft Fire Safety Demonstration Project

Summary of Activities



National Aeronautics and Space Administration

Spacecraft Fire Safety Demonstration Project

Testing and Demonstration of Technologies

	Technology Need	Current capability	Demonstration capability
Material Flammability	• *Low- and partial-g flammability limits for spacecraft materials*	• *Zero Gravity Facility*	• Microgravity Science Glovebox (ISS) • Large-scale demo
Fire Signatures and Detection	• *Hybrid gas and particulate sensors* • *Common detectors*	• *Normal-g test facilities (WSTF, GRC)*	• Microgravity Science Glovebox (ISS) • Nanoracks facility (JSC) • Large-scale demo
Fire Suppression	• *Realistic fire challenges*	• *ISS Rack Mock-up*	• Modeling and analysis
Post-fire response and monitoring	• *Post-fire gas sensors* • *Smoke-Eater*	• *Normal-g test facilities (WSTF, GRC)*	• Large-scale demo

Spacecraft Fire Safety Demonstration

- *Flammability limit verification*
- *Large-scale flame spread*
- *Demonstrate SFS technologies*

Burning and Suppression of Solids (BASS)

- PI: Dr. Paul Ferkul (*NCSER)*
- Co-I: Professor James T'ien, *(Case Western Reserve University),* Fumiaka Takahashi (*NCSER)*, Dr. Sandra Olson (NASA GRC)
- BASS is an experiment being performed in the Microgravity Science Glovebox on ISS
- Selected as a Rapid Turnaround Experiment and makes use of the SLICE hardware.
- ISS operations began in March 2012
- Developing flammability maps as a function of velocity
- Samples include:
  - Nomex (two kinds)
  - Ultem film
  - Cotton/fiberglass fabric
    - Candidate large sample fuel
  - Plexiglass spheres and sheet
  - Wax candles and slabs
- Fire Suppression testing
  - Nitrogen jet extinguishment

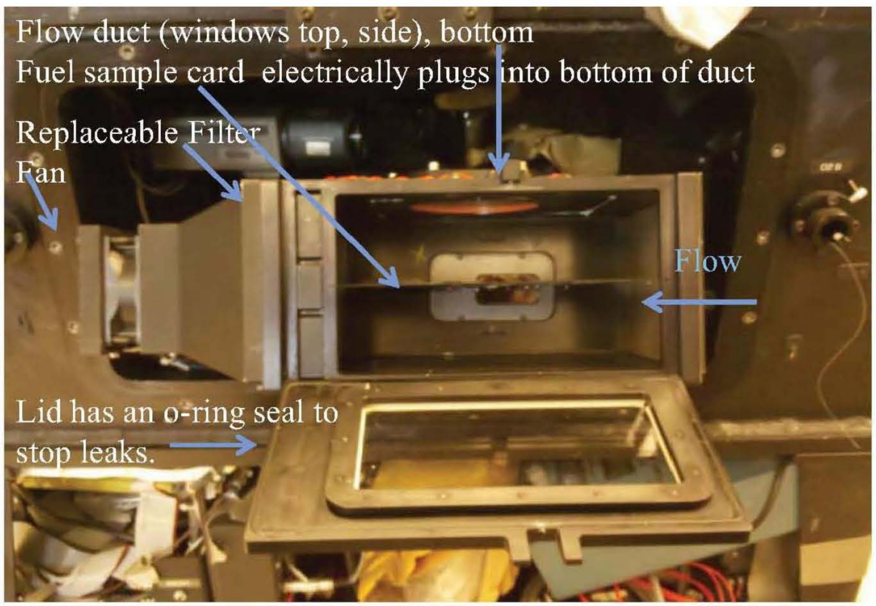
1- and 2-cm diam PMMA spheres

1- and 2-cm wide flat samples (cotton-fiberglass, Nomex, Ultem)

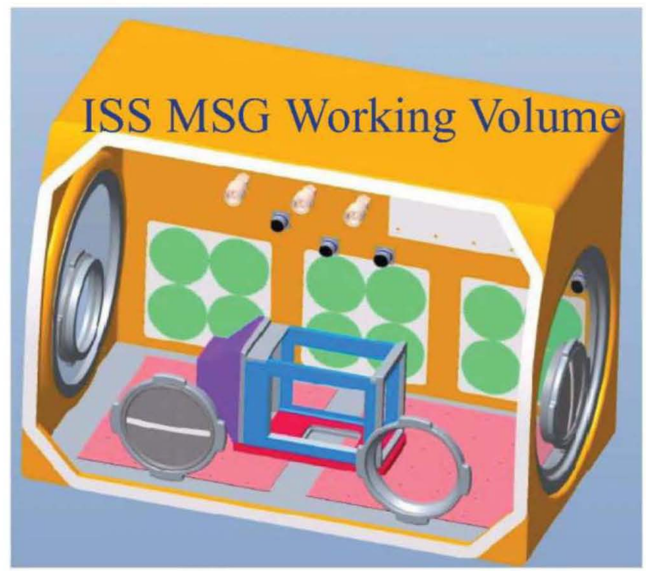
Flow duct for the SPICE/BASS experiment in the ISS MSG

BASS-II

- Develop a larger flow duct while utilizing some of the SLICE/BASS hardware
  - Flow system to vary velocity
  - Use ISS N_2 to blend down MSG working volume to decrease $\%O_2$ (~12-24 $\%O_2$)
- Conduct flammability limit experiments – one of the objectives of the large-scale experiment
- Feasibility of developing this experiment capability is being investigated in the SFS Demo project



TIGER flow duct features. *Duct is imaged from above with lid open. Duct was housed in a large chamber so the ambient atmosphere could be modified (up to 50%O_2).*

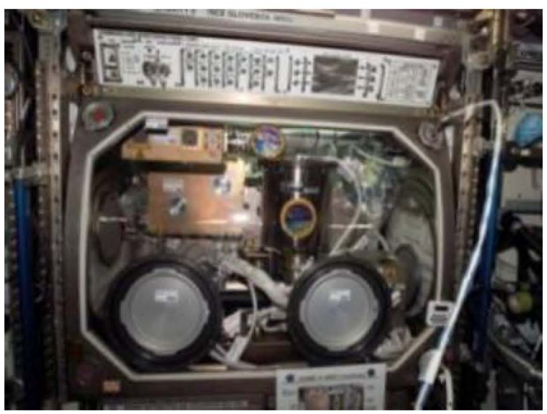


CAD rendering of flow duct in the MSG working volume

SAME – III

Smoke Aerosol Measurement Experiment - III

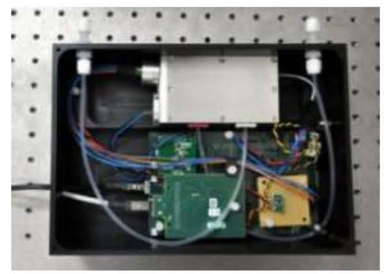
- Evaluate the performance of a next generation spacecraft fire detection system in microgravity smoke conditions
- Establish the chemical and particulate signatures of the microgravity smoke from spacecraft materials
- Technologies include:
  - *Optical Particle Counter*
  - *Second-generation Multiparameter Aerosol Scattering Spectrometer*
  - *Development and testing of solid-state sensor package*
  - *CO sensor using 7W 4.6-micron QC laser*
  - *Tunable laser-diode post-fire monitor*



Smoke Aerosol Measurement Experiment in the Microgravity Science Glovebox on ISS

Potential Instruments

Miniaturized Optical Particle Counter (mOPC) (GRC)



2.3 μm VCSEL-WMS CO detector. (Vista Photonics)

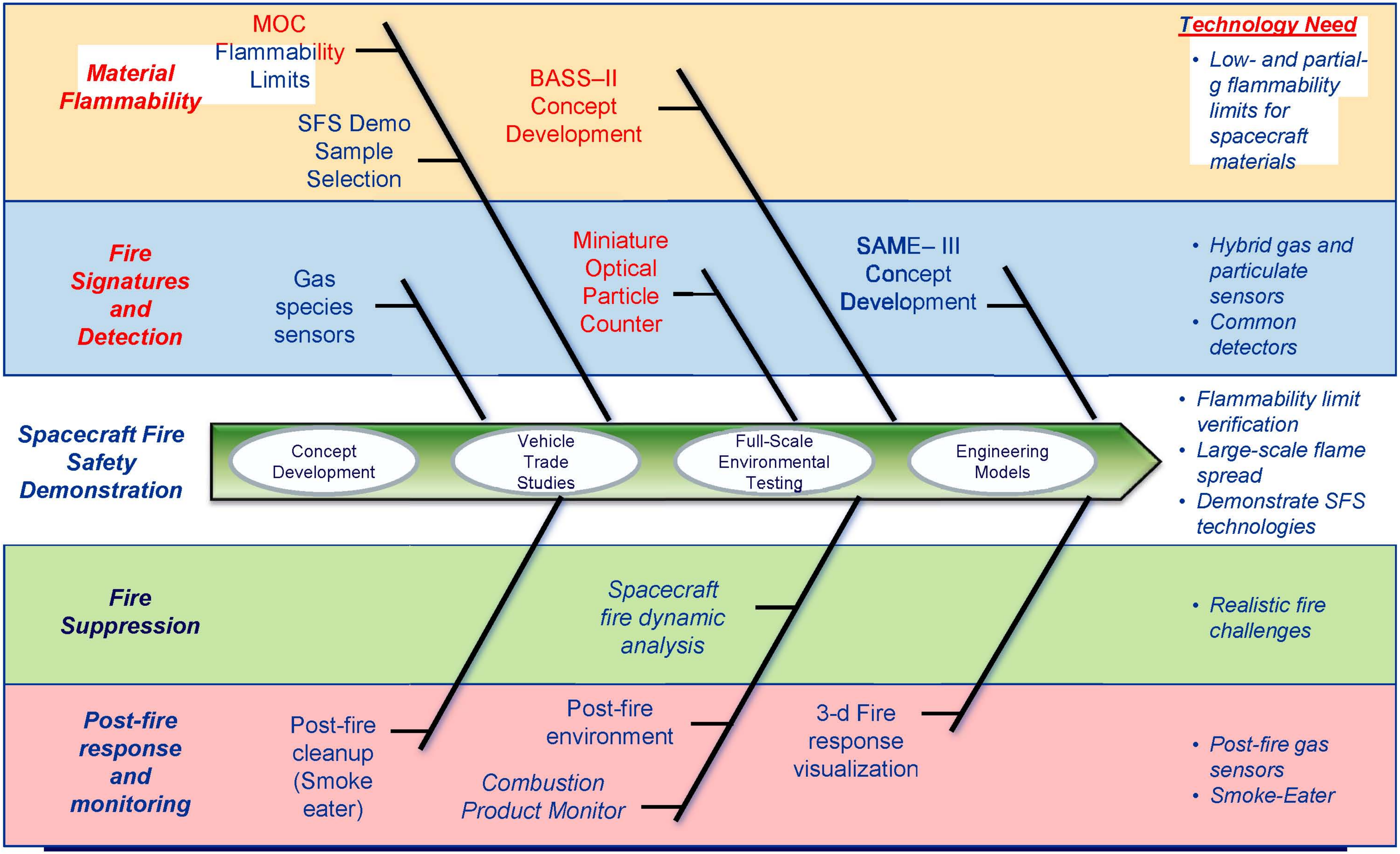
QCL-based CO sensor (JPL)

Handheld Combustion Product Monitor (Makel Engineering, Inc.

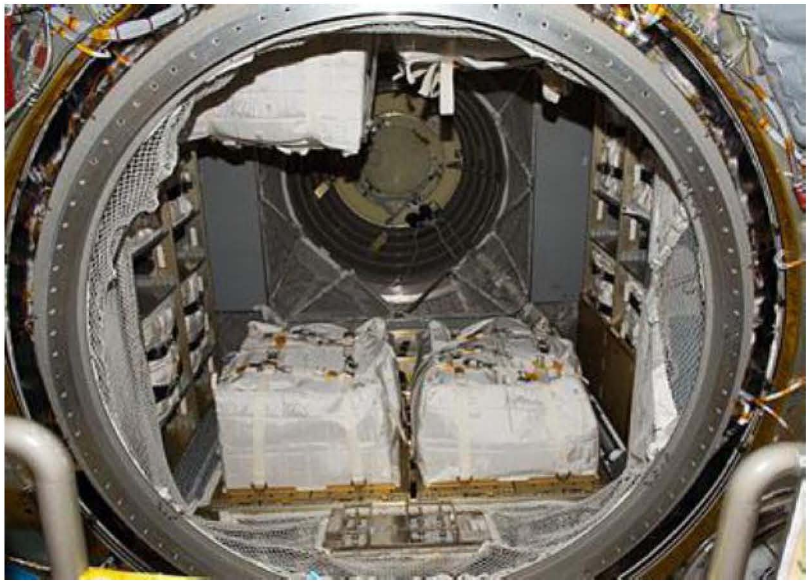
Multi-species gaseous fire detection (Makel Engineering, Inc.)

Spacecraft Fire Safety Demonstration Project

Summary of Activities



Mission Concept



Load onto an ATV in a cargo bag

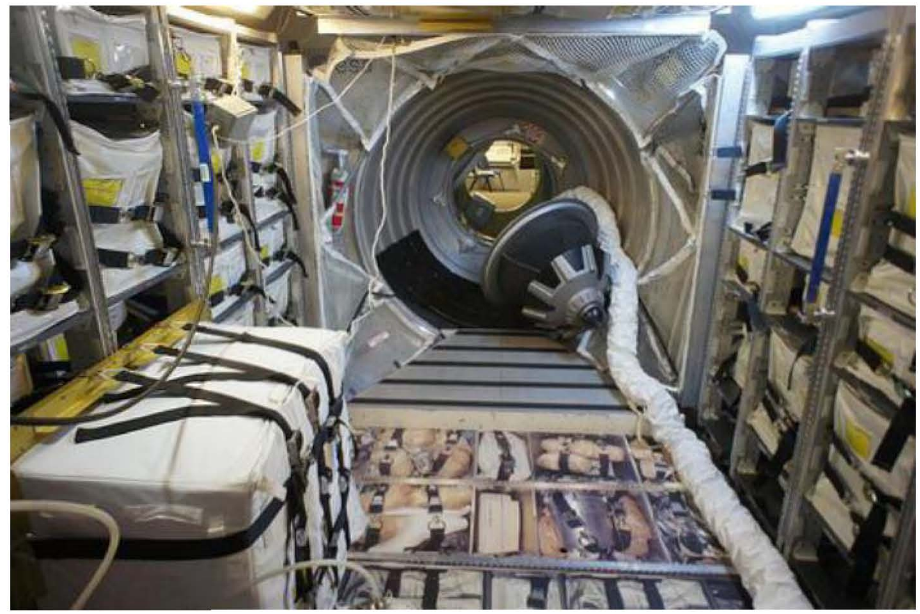
ATV in shroud on an Ariane V

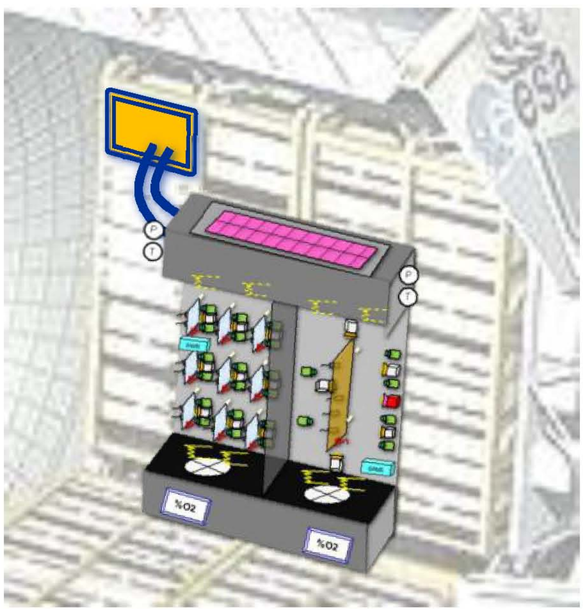
Ariane V launch

Mission Concept

Dock to ISS

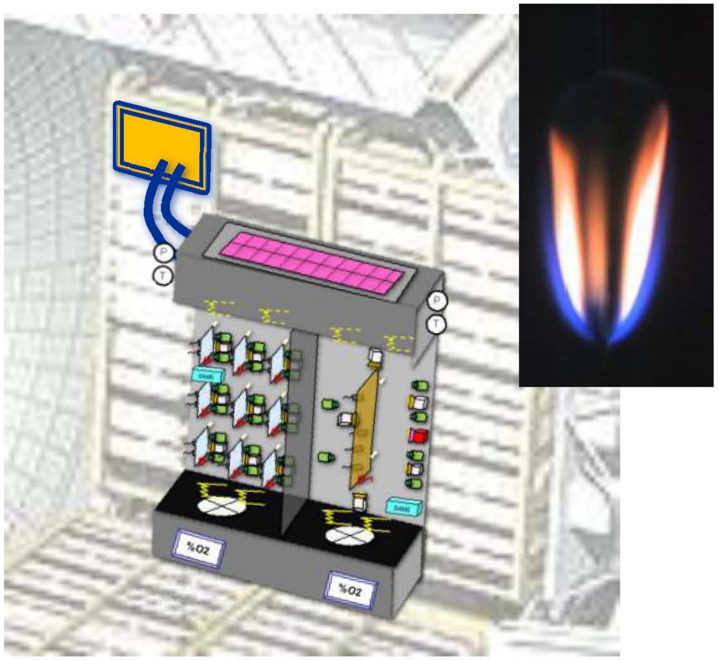
Unpack cargo, reload with trash



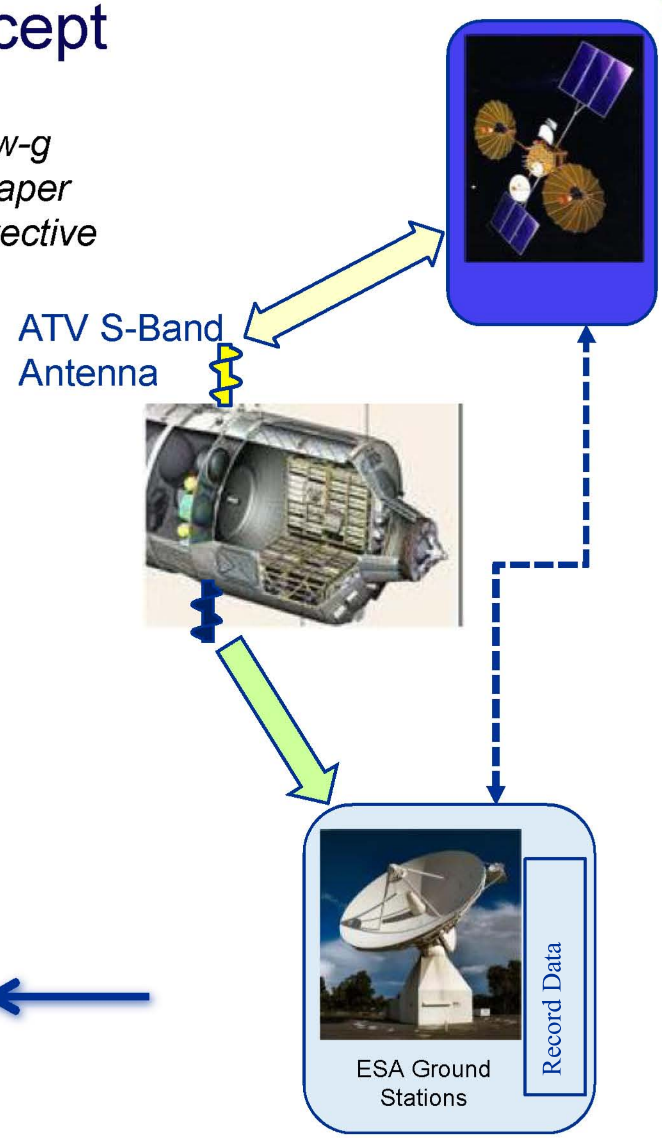


Unstow SFS Demo experiment, assemble experiment on plates on front of racks, and perform check-out

Mission Concept

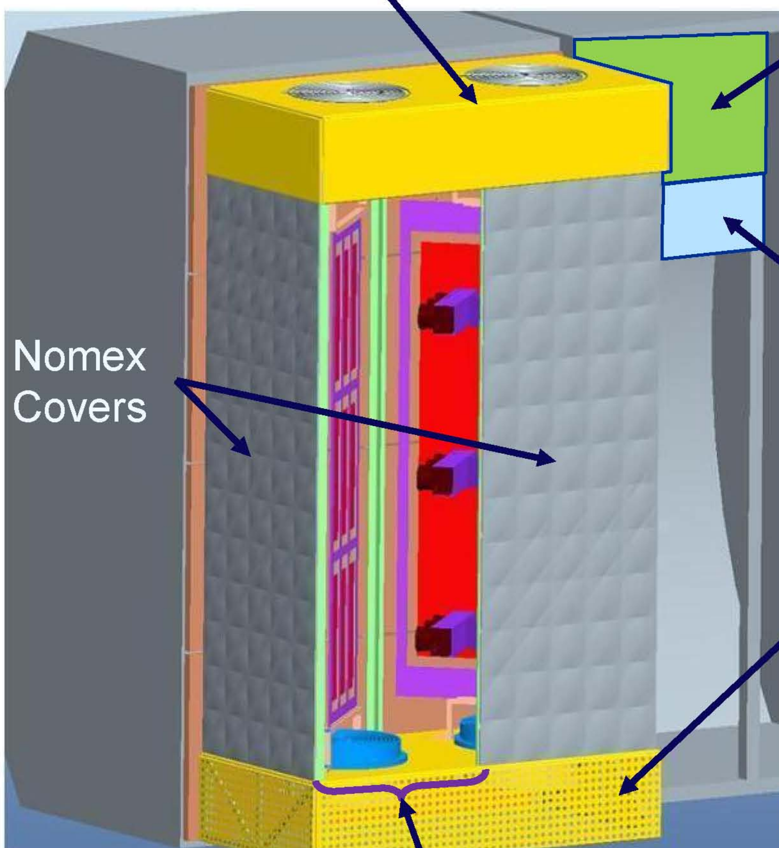


Side view of a low-g flame on a thin paper sample in a convective flow



ATV-1 re-entering the atmosphere

Experiment Physical Concept



ATV Interfaces:

1. To External Mounted SFSDP Antenna
2. Command Inputs Issued by ESA
3. Structural for Mounting Hardware

Flow Straightener Section

Also contains:

- O_2 sensor
- Pressure Sensor
- Inlet air temperature sensor

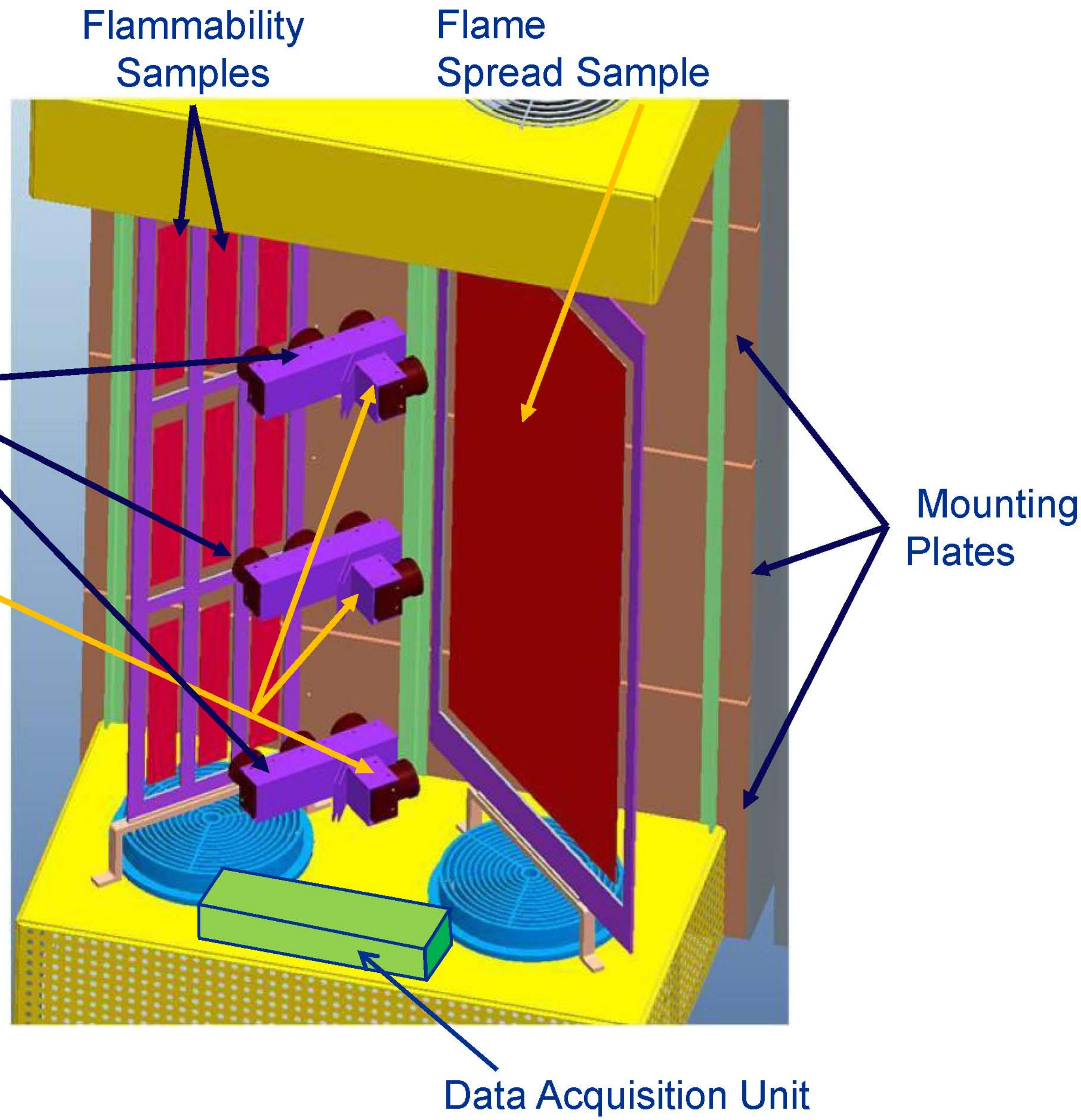
<u>Not Shown:</u>

- Interconnecting Cables
- S-Band Antenna
- Attachment Hardware

Not to Scale

Experiment Test Section

- Camera array assembly (typ.)
  - one camera on each *flammability* sample
  - three camera array on *flame spread* sample



Not Shown:
- Lighting
- Radiometers
- Thermocouples
- Anemometers
- Igniters
- O_2, CO_2 and CO sensors

Not to Scale

Vehicle Trade Studies

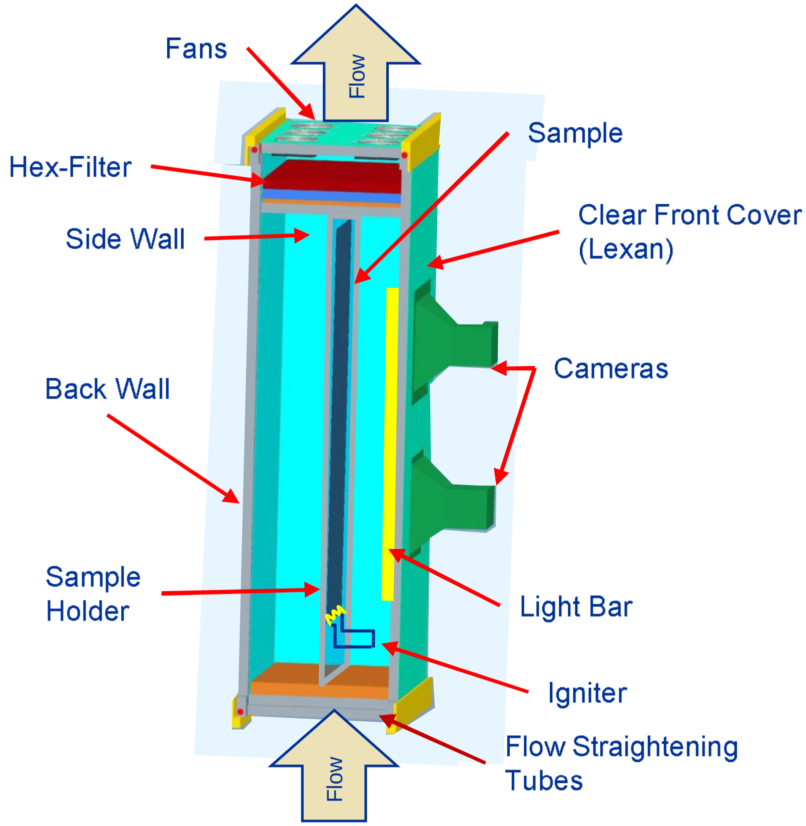
- Project began with a "clean sheet of paper" with regards to the vehicle we would use
- The ATV concept was developed because of ESA's interest in the experimental concept
  - Not necessarily because of the engineering or programmatic feasibility
- Other vehicles may also be viable options to meet all or some of the objectives of this experiment
  - HTV, Dragon, Cygnus, …
- SpaceX Dragon
  - Re-entry capsule that will return cargo from ISS
  - Reuseable capsule
    - Neither NASA nor SpaceX was interested in having cargo contaminated to an unknown degree by combustion products
  - Future DragonLab cost prohibitive; does not dock with ISS
- Orbital Sciences Cygnus
  - ISS re-supply vehicle that burns up upon re-entry
  - SFS Demo team has met with Orbital personnel to evaluate the feasibility
  - Visited Wallops Flight Facility to Orbital's facilities and the Pressurized Cargo Module

Status

- ESA/ATV kicked off an ATV Feasibility Study Team in late October 2011 to assess the feasibility of the experiment on the ATV
- Through November and December 2011, project personnel held several telecons with the Feasibility Study Team to provide information about the concept
  - Experiment configuration
  - Communications
  - Mass, Power, Volume
  - Heat Release
  - Pressure Rise
  - Concept of Operations
- Through May, project was considering ATV-5 (launch in March 2014)
- Project and AES Program Office could not converge on funding and scope of experiment
  - ATV-5 option became too risky given cost and schedule
- Current objective is to produce a “simple” modular test facility that could be reproduced and fly on multiple flights
  - Achieve additional demonstration objectives while achieving a lower cost per flight

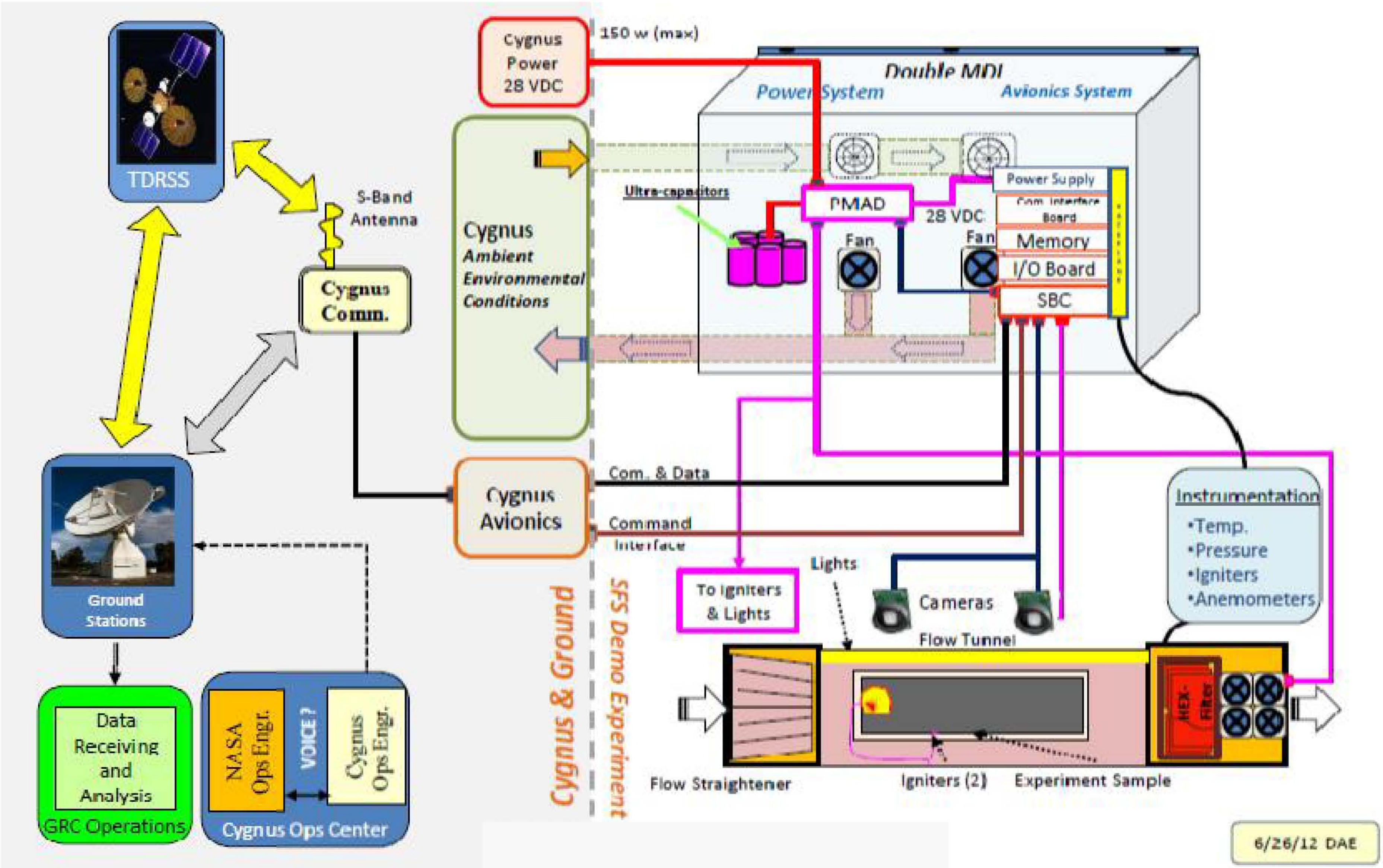
Status

- Developing an experimental concept for the Cygnus vehicle
- Multiple, single-objective experiments
  1. Single, large sample – large-scale flame spread
  2. Flammability limit samples – verify depression of oxygen flammability limits in low gravity
     - Increase (or lower) %O_2 in Cygnus
  3. Repeat 1. or 2. at different conditions/post-fire clean-up
- Orbital Sciences is evaluating costs for integration and operations
  – Plan flights every 6 months starting in December 2014



Details of experiment flow duct (tentative).
Interior of flow duct is 20” x 20” x 48”

Architecture Overview – Flight Element

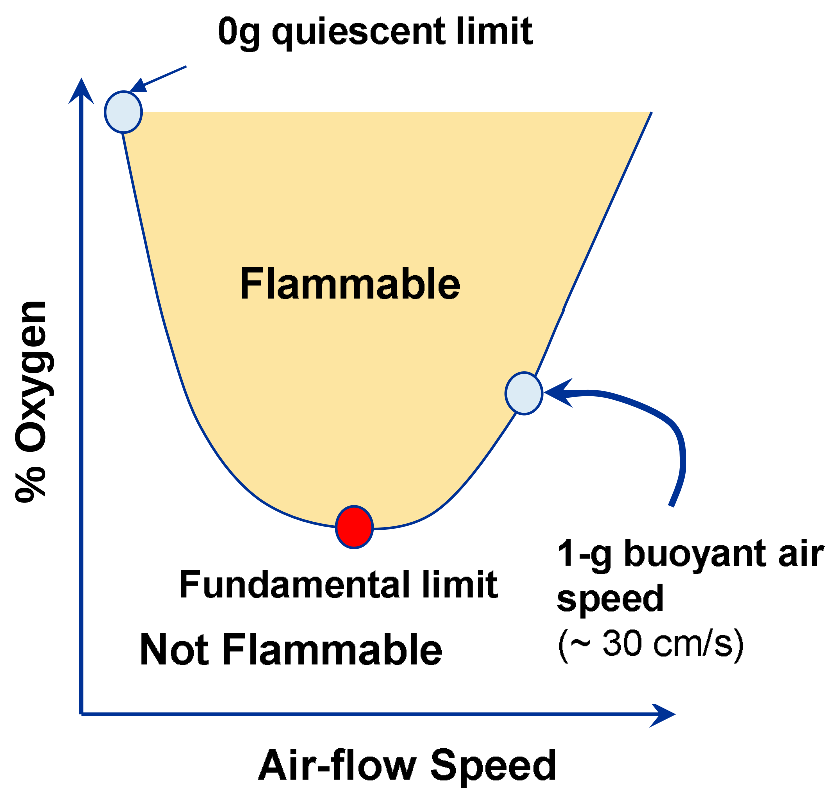


Summary

- Recent studies and analyses have confirmed the fire safety needs for long-term exploration missions
- Current work in the Spacecraft Fire Safety Demonstration Project has allowed us to advance fire safety demonstrations in numerous areas
  - Vehicle/operational limitations prohibit a comprehensive large-scale fire experiment
- Approach is to develop technologies and then test in a suite of demonstrations
  - Ground-based: post-fire environment characterization, post-fire monitors, fire scenarios, fire signatures
  - Space-based (ISS): material flammability limits, fire detection,
  - Space-based (Re-entering vehicle): large-scale flame spread, material flammability limits
- ATV-5 flight option became impractical because of schedule
  - AES Program Office requests a smaller, modular experiment that could be reproduced on several flights
- Project team is developing a concept for Orbital Science’s *Cygnus* vehicle
  - Develop resource estimate by mid-August

Experiment Justification

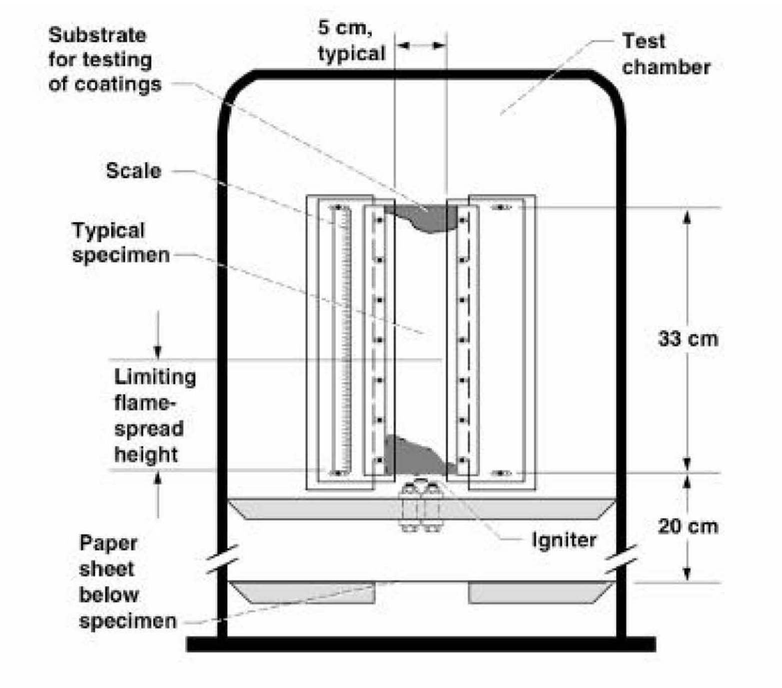
- How different are low-g material flammability limits from those measured in normal gravity?
  - Low-gravity oxygen flammability limits are different in low-gravity than in normal gravity
  - Normal gravity flames induce a natural convective flow that transports oxygen to the flame *but also removes heat*
  - Forced convection in low-g transports oxygen to the flame but rate of heat removal is reduced
    - The normal-gravity (and partial-gravity, for that matter) oxygen concentration flammability limit is not necessarily the minimum



- What is the fate of a large-scale fire in low-gravity?
  - Extrapolation of observed low-g flame behavior to a full-scale spacecraft fire scenario is tenuous
  - Experience with “significant” fires is very limited
    - Enhance risk assessments and modeling of fire events

Experiment Justification

- NASA-STD-6001 describes the test methods used to qualify materials for use in space vehicles.
- The tests cover flammability, odor, off-gassing, and compatibility.
- The primary test to assess material flammability is Test 1: Upward Flame Propagation



Test 1 Apparatus

- Materials "pass" this test if the flame self-extinguishes before it propagates 15 cm
- Maximum oxygen concentration (MOC) is defined as the highest O_2 at which material passes Test 1
- Flammability limits determined by this test are strongly influenced by natural convection
- Samples are 5 cm wide x 33 cm long and rigidly held in a frame

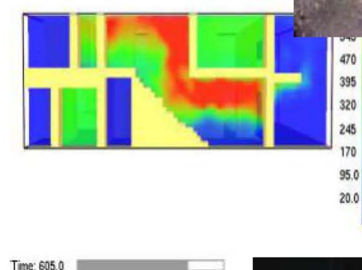
➢ *Flammability samples*

How rapidly can a fire spread in low-g?

- This question lies at the heart of the development of a fire safety strategy
  – Terrestrial or spacecraft applications
- Rate of fire growth impacts:
  – Time to detect
    - Early detection reduces impact of fire, response strategy
  – Size of fire
    - Amount of fire suppression agent required
  – Heat release rate, fire spread to surrounding materials
    - Collateral damage
  – Emission of combustion products
    - Post-fire cleanup strategy and consumables

➢ Large-scale *flame spread* sample
  – 0.5 m wide x 1.0 m long

NIST Full Scale Fire test



FAA full scale aircraft test

Side view of a low-g flame on a thin paper sample in a concurrent convective flow